

# HEAT RETENTION OF A PHOTOVOLTAIC/ THERMAL COLLECTOR WITH PCM

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## ABSTRACT

A novel PV/T/PCM system that generates electricity, stores heat and pre-heats water was characterised under outdoor conditions in Dublin, Ireland. The system design combines a PV module with a thermal collector; in which heat is removed from a heat exchanger embedded in PCM through a thermosyphon flow. System performance was compared against a) the same system without PCM, b) the same system without heat exchanger or PCM, and c) the PV module alone. It was shown that the temperature attained by the water was approximately 5.5 °C higher when compared to a PV/T system with no PCM. PCM are shown to be an effective means of storing heat for later heat removal in a PV/T system.

## ABBREVIATIONS

PV, Photovoltaic; PV/T, Photovoltaic/ thermal; PCM, Phase change material; PV/T/PCM, Photovoltaic/ thermal/ phase change material; DSC, Differential scanning calorimetry; THM, Temperature-history method

## KEYWORDS

Photovoltaic, photovoltaic/ thermal system, phase change material, thermal energy storage

## 1 INTRODUCTION

### 1.1 PHOTOVOLTAIC/THERMAL COLLECTORS

Photovoltaic (PV) modules convert solar energy directly to electricity whereas solar thermal collectors absorb solar energy to heat air or water. In a photovoltaic/ thermal (PV/T) collector PV generates electricity and forms the absorbing surface of a solar thermal collector with heat generated transferred to air or water for space or water heating applications. The objective in PV/T collectors is to achieve an optimal simultaneous useful electrical and heat output. PV/T systems can generate electricity and heat simultaneously. Typically 15 % – 18 % of solar radiation incident on a PV module is converted to electricity and 82 % – 85 % is converted to heat. This study investigates the experimental thermal performance of a PV/T system that by

incorporating a phase change energy storage material allows delivery of the heat from the collector to be deferred.

The PV/T collector concept was initiated by Wolf (Wolf, 1976) subsequent investigations have considered flat plate (Kern and Russell, 1978, Florschuetz, 1979, Cox and Raghuraman, 1985, Lalović et al., 1986) and concentrating (Hamdy et al., 1988) PV/T collectors. PV/T systems became a major area of interest since the 1990's (Charalambous et al., 2007, Zondag, 2008, Chow, 2010, Chow et al., 2012, Zhang et al., 2012, Browne et al., 2015a, Kumar et al., 2015) with research focused on PV/T system design, simulation, modelling and testing (Garg et al., 1990, Hayakashi et al., 1990, Agarwal and Garg, 1994, Hammad, 1994, Prakash, 1994). Use of thermosyphon flow, as employed in systems detailed here, is common place in close-coupled solar water heaters (Norton and Probert, 1986, Norton, 2011).

## 1.2 USE OF PCM IN PV APPLICATIONS

Phase change materials (PCMs) have been used extensively for thermal energy storage (TES) (Cabeza et al., 2011, Navarro et al., 2016a, Navarro et al., 2016b). At initial heating, a PCM heats sensibly and when the PCM reaches melting/solidification temperature, the material absorbs latent heat, progressively melting. Melted material continues to warm further as the material melts. The duration and temperature range over which the phase change takes place depends on the mass, latent heat capacity and thermal conductivity of the PCM and any enhanced heat transfer elements therein. Once it has completely changed phase, the PCM heats sensibly. The selection criteria for a PCM to be used for heat storage in a PV/T system for regulating PV temperature are listed in Table 1 (Hasan, 2010a). Numerous in-depth descriptions of the thermophysical properties of PCMs are available (Zalba et al., 2003, Sharma et al., 2009, Cabeza et al., 2011).

**Table 1: Desired PCM properties for heat storage in a PV/T system (adapted from Hasan, 2010a)**

		Requirement	Rationale
	Thermal	High latent heat High heat capacity Good thermal conductivity Reversible phase change Fixed melting point	Maximum heat absorption Minimum sensible heat Efficient heat removal Diurnal response Consistent behaviour
	Physical	Congruent melting Low volume expansion High density No supercooling Good crystallisation rate	Minimum thermal gradient No overdesign Low containment requirement Easy to freeze Faster solidification rate

Property	Chemical	Chemical stability Non-corrosive Non-flammable Non-explosive Non-toxic	Long life Long container life Comply building safety codes Environment friendly
	Economic	Abundant, Available Cheap and Cost effective	Market competitiveness Economic viability and market penetration
	Environmental	Recyclable/ Reusable Odour free	Ease of disposal/ reuse Comfortable to apply in dwellings environment

PCM has been used for thermal management of PV ([Huang et al., 2004](#), [Huang et al., 2006a](#), [Huang et al., 2006b](#), [Huang et al., 2006c](#), [Hasan, 2010b](#), [Hasan et al., 2014](#), [Sarwar et al., 2014](#), [Browne et al., 2015b](#), [Hasan et al., 2015](#)). In a solar thermal collector the distribution of heat from the collector is immediate. However, in a PV/T/PCM collector the heat is stored in the collector for later distribution. A prototype PV/T system with integrated PCM heat storage stores heat during the day and discharges heat to water at night has been investigated experimentally ([2013a](#), [Browne et al., 2013b](#), [2014](#), [2015a](#)).

A one-dimensional energy balance model of a PV/T/PCM system found the optimum thickness for PCM to be 0.03 m which increased PV efficiency by approximately 6.5 % compared to a PCM thickness of zero meters ([Malvi et al., 2011](#)). The PV output increase of 9 % compared to a reference PV based on a system containing 10-15 panels. Further investigation was carried out into the optimum water flow rate, applicable PCM melting point and PCM conductance ([Malvi et al., 2011](#)).

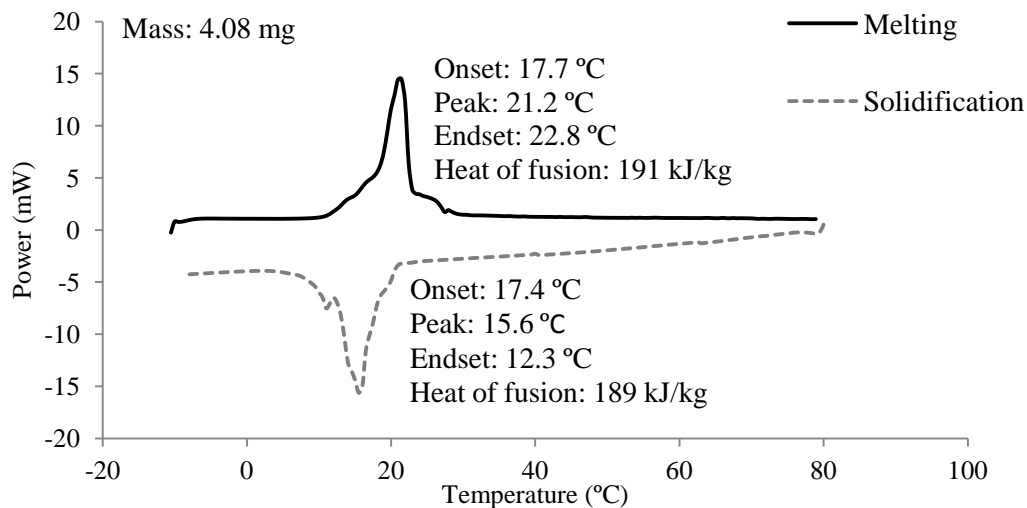
A model for a domestic PV/T system with a phase change heat storage unit was experimentally validated ([Yin et al., 2013](#)). Water is directly heated by thermal energy from the PV during the day where it can (i) be used immediately or (ii) if heat is not immediately required the PCM will store heat for later use ([Yin et al., 2013](#)). During hot months, heat captured by the PCM is prevented from entering the dwelling, significantly lowering the dwelling's cooling load.

A numerical simulation of BIPV/T/PCM vented and unvented Trombe-Michel walls using Matlab/Simulink was validated via comparison with experimental results from a BIPV/T system; ([Aelenei et al., 2013](#), [Aelenei et al., 2014](#)) for an unvented wall PCM decreased wall

temperature by 7 °C when compared to a system without PCM showing the PCM stored a significant amount of heat. In a vented system, the cavity temperature showed a negative difference of 2 °C compared to a reference as heat was removed by ventilation and not stored.

## 2 PHASE CHANGE MATERIAL CHARACTERISATION

The laboratory scale thermophysical characterisation tests for phase change are differential scanning calorimetry (DSC), differential thermal analysis (DTA) (Zalba et al., 2003) and, for larger sample sizes, the temperature-history method (Yinping et al., 1999). The PCM used in System 1 was a eutectic mixture of capric and palmitic fatty acids (CP). The thermophysical properties during the melting and solidification cycles, found using the differential scanning calorimetry (DSC), are presented in Figure 1 and Table 2. Charging occurs when the PCM melts from 17.7 °C to 22.8 °C. Discharging occurs from 17.4 °C to 12.3 °C.

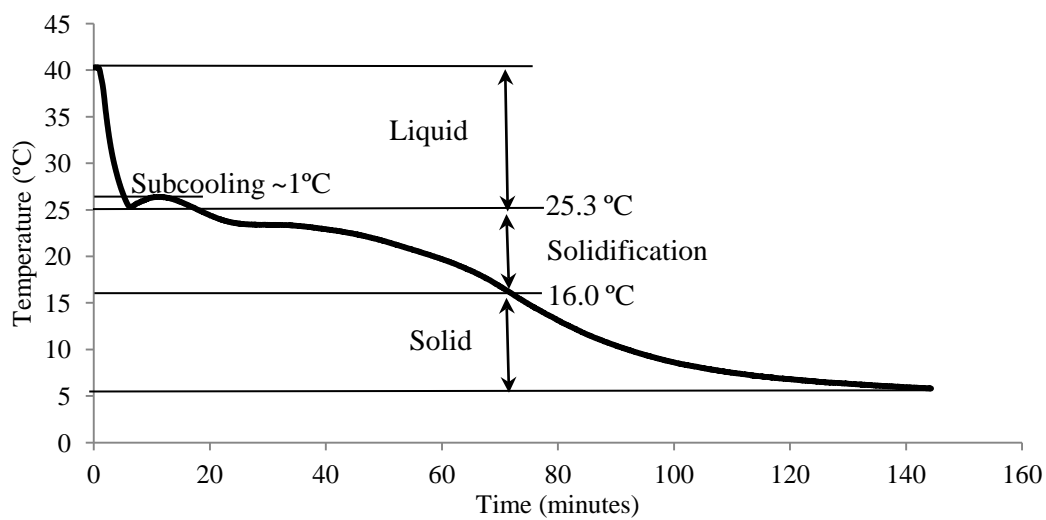


**Figure 1: Differential scanning calorimetry of capric: palmitic acid during melting and solidification**

**Table 2: Thermophysical properties of capric: palmitic acid (75%:25 % weight)**

		Capric: palmitic acid
Property	Melting range (°C)	17.7-22.8
	Solidification range (°C)	12.3-17.4
	Heat of fusion (kJkg <sup>-1</sup> )	189 - 191
	Thermal conductivity (Wm <sup>-1</sup> K <sup>-1</sup> )	0.143
	Specific heat capacity (kJkg <sup>-1</sup> K <sup>-1</sup> )	1.65

[Yinping et al. \(1999\)](#) identified that the shortcomings in the DSC method of characterising PCM included (i) potential unrepresentativeness of the small 1 mg to 10 mg samples, (ii) the sample size and geometry dependence of the thermophysical properties of some PCM, (iii) the complexity and cost of the analysis instrumentation, and (iv) that the phase change cannot be observed visually. Unlike the DSC test, the temperature-history method (THM) determines the heat of fusion, specific heat and thermal conductivity of phase change materials which uses much larger sample sizes using a simpler experimental technique in which phase change can be observed visually. The results of a THM investigation on capric: palmitic acid is presented in Figure 2.



**Figure 2: Temperature history curve for capric: palmitic (55: 45 by % weight) acid**

In the temperature-history method experiment, the PCM was heated to 40 °C and maintained at that temperature for one hour to bring the entire sample to a uniform temperature. The tube containing the PCM was removed from the heating bath. The temperature of the PCM during cooling was measured. The onset of solidification was observed at 25.3 °C with approximately 1 °C of supercooling. The completion of phase change occurred at 16.0 °C when the material had solidified. (The minimum gradient at that temperature indicated completion of phase change ([Hong et al., 2004](#))). The phase change range is 16 °C to 25 °C and the latent heat of fusion 210 kJ/ kg. The specific heat capacities of the solid and liquid phase are 1.45 kJ/ kg and 1.65 kJ/ kg, respectively.

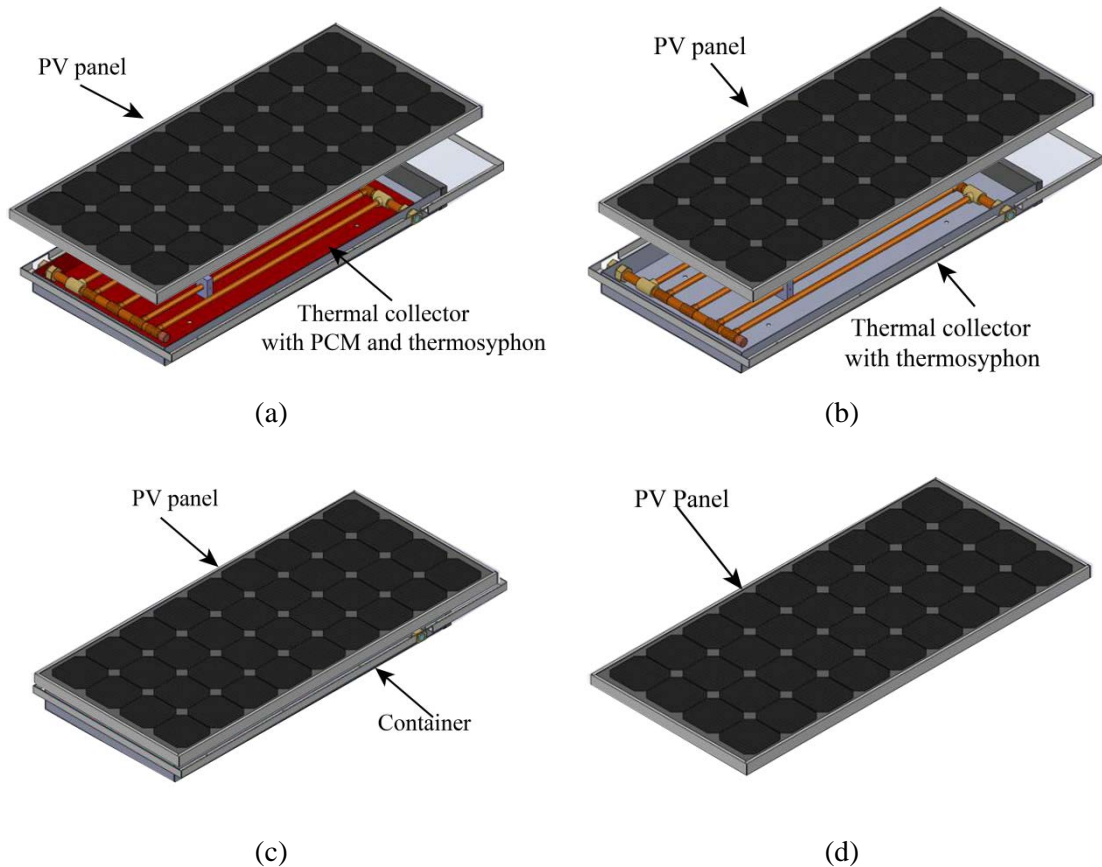
These results agree with those previously published ([Kenisarin and Mahkamov, 2007](#), [Sarı and Karaıpekli, 2008](#), [Hasan, 2010b](#)) where the melting point and heat of fusion are reported as 21.85 °C - 22.3 °C and 171 kJ/ kg - 196 kJ/ kg, respectively.

### 3 OUTDOOR EXPERIMENTS

A large-scale outdoor PV/T/PCM system was designed, installed and characterised experimentally in Dublin, Ireland (53.33 N, 6.24W). The aim of these experiments is to analyse the thermal behaviour of a PV/T/PCM system in concomitant comparison with that of three reference systems (Browne et al., 2013a).

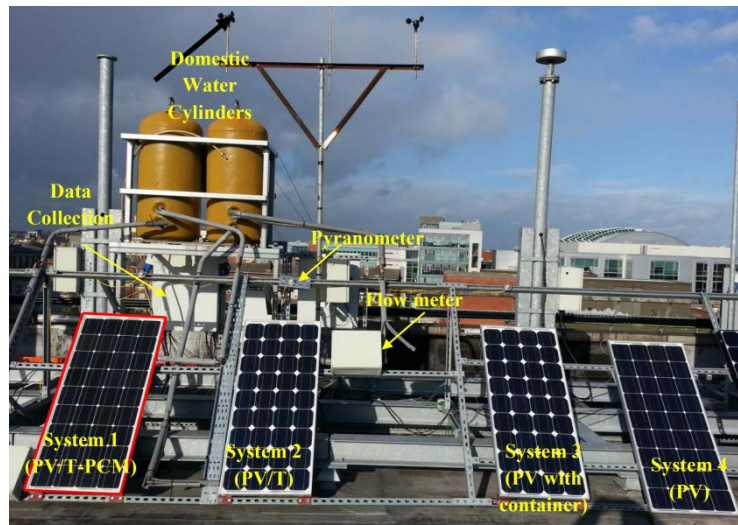
### 3.1 FABRICATION OF EXPERIMENTAL SYSTEM

A stepped approach was taken when designing the experiment, starting from the reference, System 4 (PV panel only), and building on System 4 to produce System 3 with an added heat sink (PV with container) to building on this to produce System 2 which included a PV with a integrated pipe network (PV/T system) and water storage tank and finally System 1 which included all previous components along with PCM energy storage (PV/T/PCM system) as shown in Figure 3. System 4 is a PV panel only and System 3 builds on this with an attached container referred to act as a heat sink. Figure 3(a) and (b) are exploded views of System 1 and System 2, respectively, with the PV panel removed for illustration purposes. System 2 includes a pipe network within an empty container (air filled) and a tank and System 1 includes the pipe network within a PCM filled container. The pipe network is clamped into position at the entry and exit points into the container allowing it to maintain its position at the face of the container and adjacent to the PV panel.

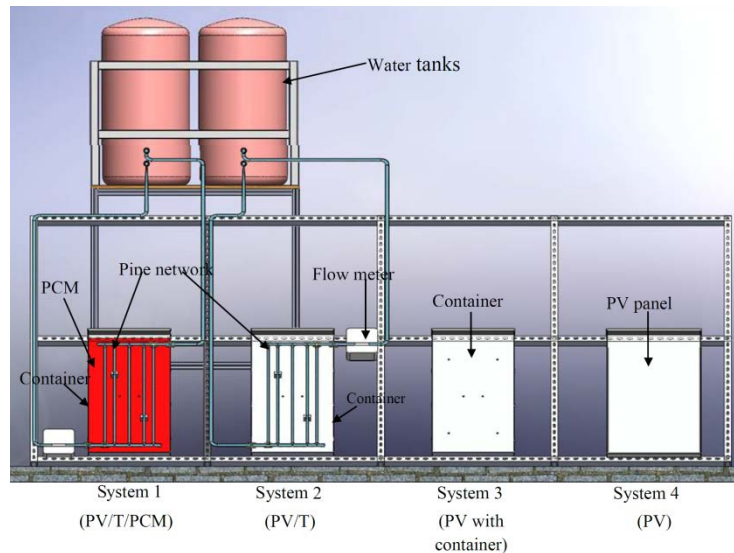


**Figure 3: Schematic illustrating the design of (a) System 1(PV/T/PCM) (b) System 2 (PV/T) (c) System 3 (PV with container) and (d) System 4 (PV) in the experiment**

Four 80W monocrystalline silicon 1.2 m x 0.508 m x 0.035 m PV panels (Solar Technology International, 2013) were characterised outdoors using an ISM 490 Solar Module Analyser (Iso-Tech, 2009) to perform within  $\pm 0.05\%$  of each other. Each of the PV panels was incorporated in each of the four systems; as illustrated in Figure 4 and detailed in Table 3.



(a)



(b)

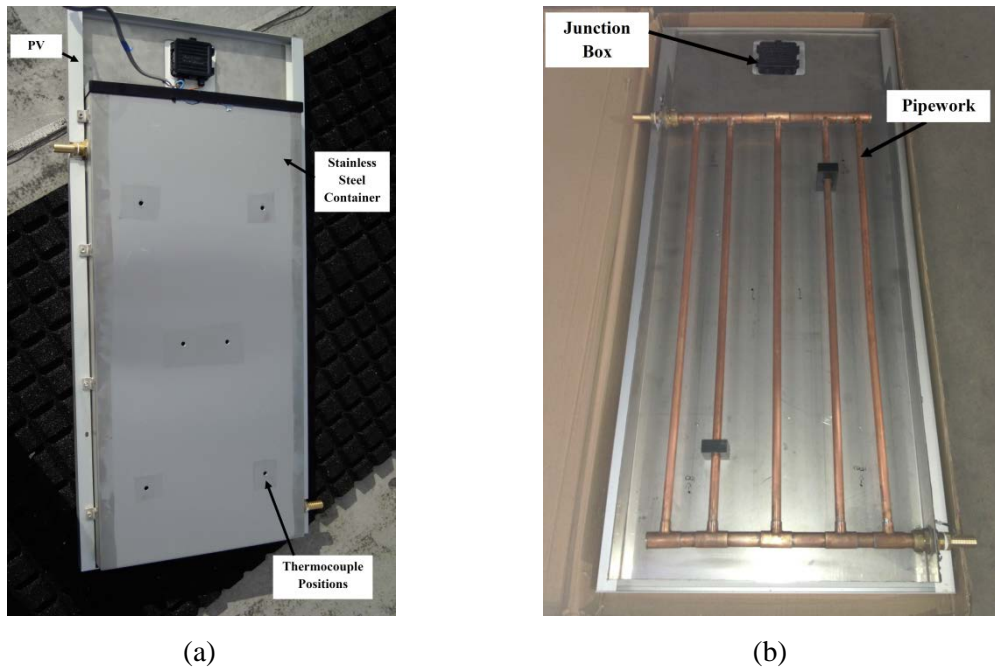
**Figure 4: (a) Photograph and (b) Schematic view of experimental set-up**

**Table 3: System attributes**



		PCM	Pipe Network	Container	PV panel
System	1	Yes	Yes	Yes	Yes
	2	No	Yes	Yes	Yes
	3	No	No	Yes	Yes
	4	No	No	No	Yes

A stainless steel (thermal conductivity of 16 W/m.K) container as shown in Figure 5(a) of dimensions 1 m x 0.471 m x 0.065 m was attached to each PV panel in Systems 1, 2 and 3. Stainless steel was used as it has a high resistance to corrosion, particularly in the temperate maritime climate of Ireland. The container was welded on all sides to ensure no PCM leakage or moisture ingress (see Figure 6). The container did not cover the junction box to avoid potential PCM ingress. The large face of the container was bonded to the back of the PV panel as shown in Figure 5(a) and (b), to increase surface area for thermal conduction with a thermal paste applied to the back of the panel to ensure good conductive heat transfer. In System 1 the container contained PCM; however in Systems 2 and 3, the container is only attached to constitute the same heat sink so valid system comparisons can be carried out.



**Figure 5: (a) Fully complete container (b) Pipe network in position in container**

As presented in Figure 5(b), the containers in Systems 1 and 2 enclosed a copper pipe network positioned in the container prior to it being sealed. The water circulated through this pipe network by thermosyphon action in a closed circuit with a domestic cylinder positioned above the PV/T and PV/T/PCM units.



The container required 28 litres of PCM. This was filled by melting capric (75 %) and palmitic (25 %) acid and pouring PCM eutectic in liquid form into the container to ensure no segregation of PCM within the container.



**Figure 6: Attachment of container to PV panel**

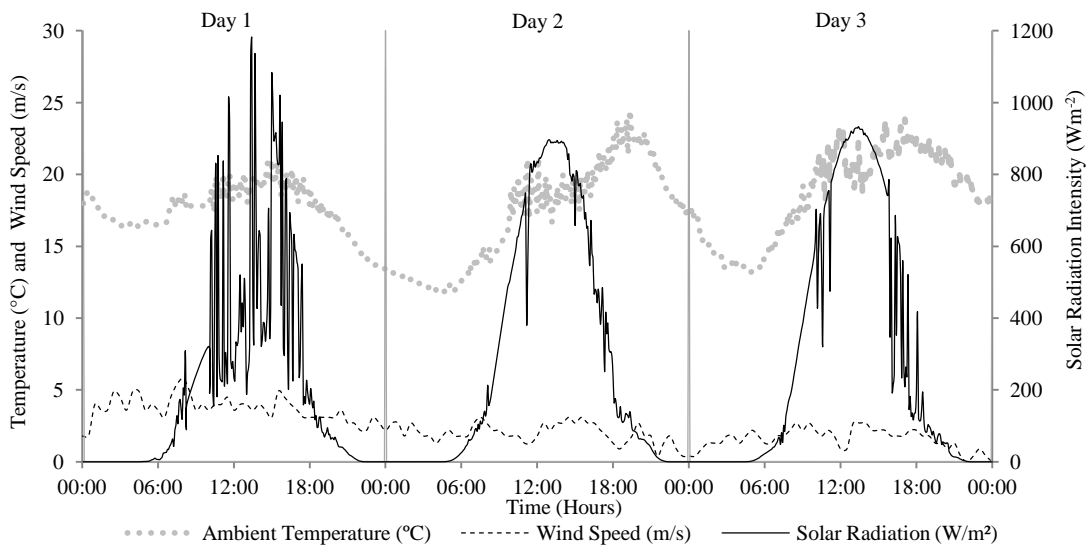
### **3.2 DATA ACQUISITION**

Solar radiation intensity on the PV front surface of each system was measured using a Kipp and Zonen pyranometer. Weather data was recorded using a Davis weather station located near the experimental rig. An IFM SU Ultrasonic flow meter was connected to each of the pipe networks to record the thermosyphon flow of water through Systems 1 and 2. PV power was measured using shunts that recorded PV current and voltage. Each system had a switch and two fuses as protective measures. Temperatures throughout all systems were measured using calibrated T-type and K-type thermocouples with a maximum deviation of  $\pm 0.5$  °C. These thermocouples were placed at the back of the PV, back of the container and inside the container. One thermocouple was placed in the front of the panel. The temperature of the water in the pipe network and cylinders were also measured. The data was recorded on 60 channel Delta-T and Agilent data acquisition systems.

The cylinders of water were emptied, re-filled and the water was initially circulated through the system on a daily basis. This ensured the water was at approximately the same temperature at the start of each experiment.

#### 4 RESULTS AND DISCUSSION

Data is presented from the 4<sup>th</sup> to 6<sup>th</sup> of July 2013, designated Day 1, Day 2 and Day 3, respectively. The weather conditions for these days are presented in Figure 7 and solar radiation was above 800 W/m<sup>2</sup> for over three hours with low wind speed of less than 5 m/s. Peak solar radiation recorded was 1177 W/m<sup>2</sup> at 13:25 hrs on Day 1, although insolation was variable due to cloudy conditions. Of the three days analysed the peak temperature was 24.4 °C at 19:20 hrs and the ambient temperature remained above 20 °C for approximately 5 hours from 16:30 hrs to 21:30 hrs, both of which occurred on Day 2. Day 3 shows that solar radiation remained above 880 W/m<sup>2</sup> for approximately 3.5 hours.

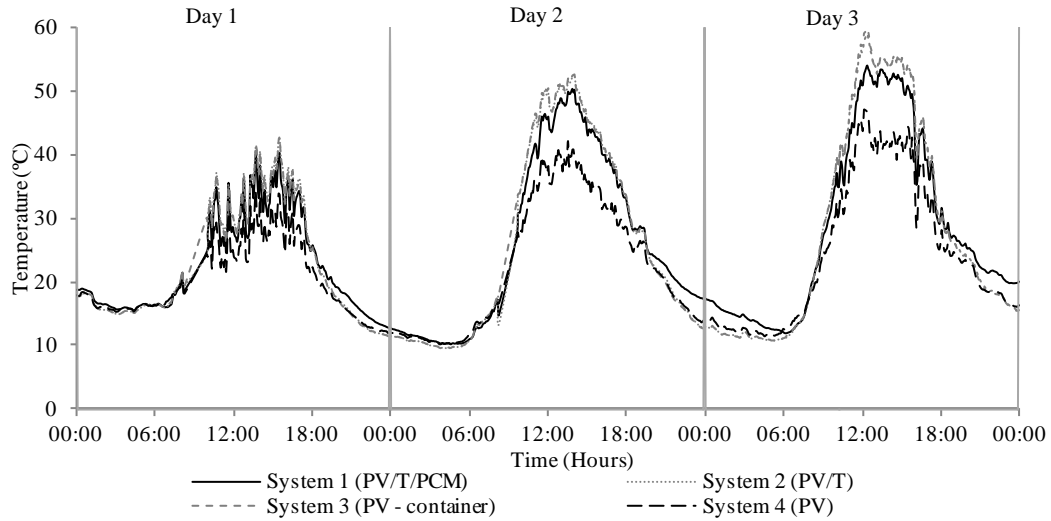


**Figure 7: Ambient temperature, wind speed measured and solar radiation measured in Dublin (53.33 N, 6.25 W) on the 4<sup>th</sup> – 6<sup>th</sup> of July 2013**

A PCM temperature of 22.8 °C was required to be reached in order for the PCM to charge fully as shown in Figure 1. Overcast conditions result in lower PV surface temperatures meaning full charging of the PCM may not occur due to minimised solar radiation. Optimum conditions for PV/T/PCM systems are high solar irradiance and lower wind speeds to ensure the PV temperature rises above the PCM melting point.

The recorded temperature of the back of the PV panel in each system is shown in Figure 8. The graph shows the elevated temperatures of each system compared with the reference, System 4. In Systems 2 and 3 empty stainless steel containers insulated the back of the PV panel so that their temperatures were higher than that of System 4 (PV). System 3 (PV/container) had an increase of more than 10 °C during Day 2 and Day 3 which was caused by the empty container attached to the rear of the PV panel reducing the effect of natural

convective cooling by wind. The addition of the thermal collector systems caused an increase in the temperature of the back of the panel, as in Systems 1, 2 and 3.



**Figure 8: Temperature on the back of the PV panel in System 1 (PV/T/PCM), System 2 (PV/T), System 3 (PV/container) and System 4 (PV)**

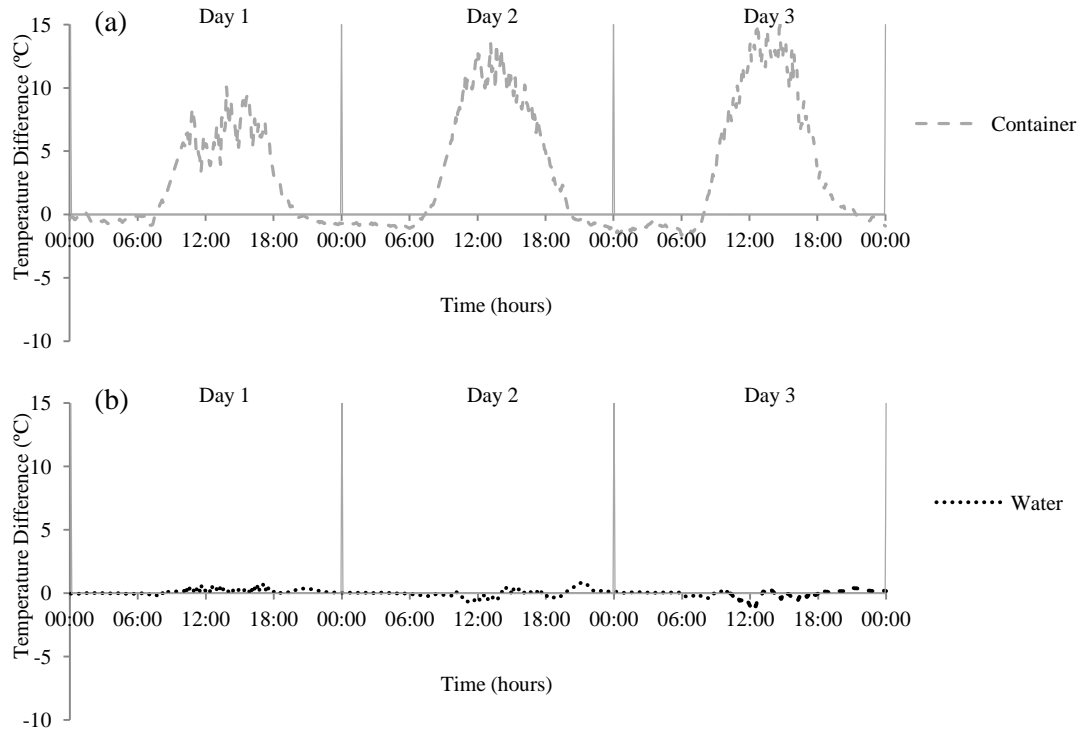
The difference between the back of the PV panel temperature in each system is presented in Figure 9, whereby (a) is ( $T_{\text{System 3}} - T_{\text{System 4}}$ ), (b) is ( $T_{\text{System 2}} - T_{\text{System 3}}$ ) and (c) is ( $T_{\text{System 1}} - T_{\text{System 2}}$ ) which represent the effect of the addition of a container, water and PCM, respectively. The difference of the temperatures of the backs of the PV panels of System 4 and System 3 is presented in Figure 9(a). This difference represents the insulating effect of the container on the back of the PV panel and shows it was increasing the temperature of the back of the PV.

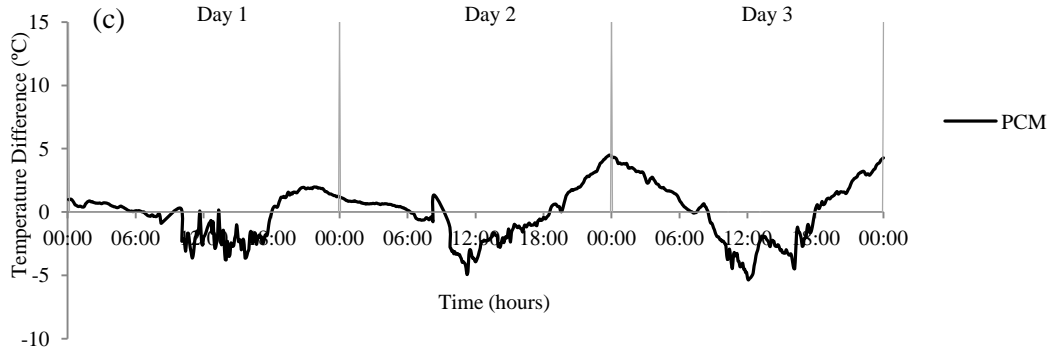
The difference between System 2 and System 3, as illustrated in Figure 9(b), shows that the water flowing through the thermosyphon inside the container had no effect on the temperature of the back of the panel. There was insufficient transfer of heat from the container to the water to affect the temperature of the back of the panel; as shown in Figure 9(b) as the temperatures of Systems 2 and 3 remained identical for the duration of the experiment.

The difference between System 1 and System 2 represents the effect of the addition of PCM to the system. As presented in Figure 9(c), the PCM slowed down the rate of temperature decrease of the back of the panel in the evening and through the night as it was storing the heat energy for release later, obviously not all heat was released to water and the increase in the temperature of the back of the panel during the night implied losses to ambient.

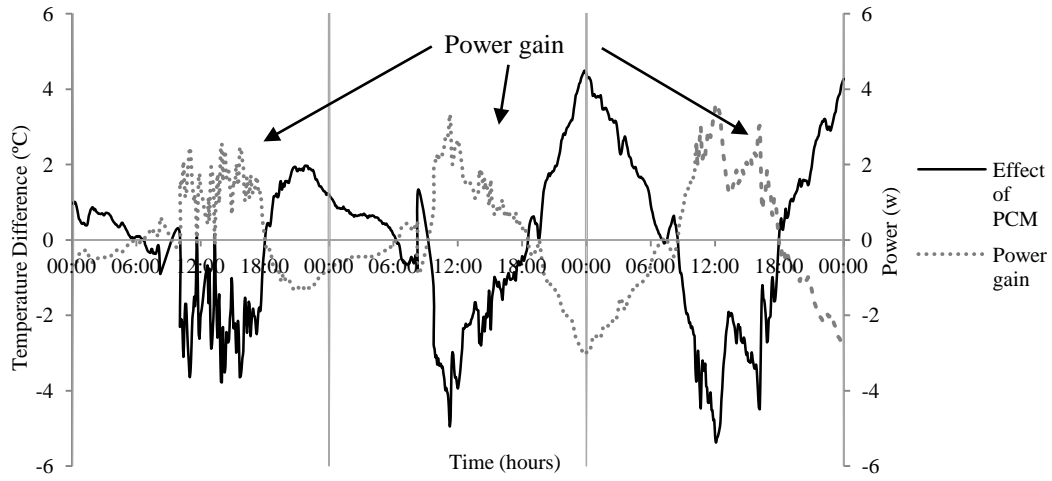
During daylight hours thermal energy generated by the PV in System 2 (PV/T), System 3 (PV with container) and System 4 (PV) was instantly available; in these systems pre-heated water should be used immediately (or stored elsewhere) otherwise the heat would be lost to ambient as there is no storage of heat in these systems.

It is apparent from Figure 9(a) that the container heated the back of the panel. However, during the periods of insolation from approximately 9:00 and 17:30 hrs, the back panel temperature was regulated by the PCM as in Figure 9(c) to give PV panel temperatures lower than the reference system without PCM. As shown in Figure 10, the electrical energy lost due to the PCM was negligible, as the insulation of the PV by the PCM occurred outside the insolation period, when there was no production of electrical energy. Considering that the power temperature coefficient of the panels used in the experiment was  $-0.675 \text{ W/ } ^\circ\text{C}$ , daily net power savings of 11.6 Wh, 13.2 Wh and 17.7 Wh were made on Day 1, Day 2 and Day 3, respectively. Power gain and coincident temperature regulation periods as a result of the addition of PCM to the system, and its ability to regulate the temperature of the PV through the absorption of latent heat, are shown in Figure 10.





**Figure 9: Effect of the addition of (a) container (b) water (c) PCM on the temperature of the back of the PV panel**



**Figure 10: Temperature regulation of PV due to addition of PCM and the power gained due to temperature regulation**

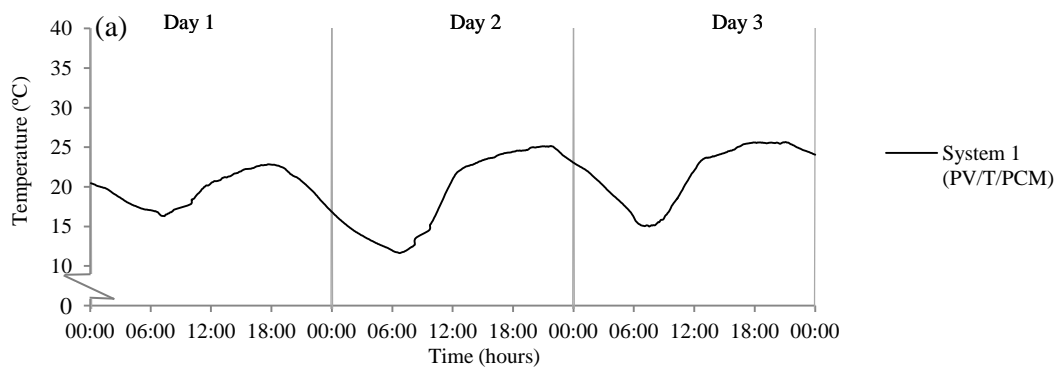
The drivers of the systems are ambient temperature and solar radiation as shown in Figure 7, which make the heat and solar energy available during daylight hours. Figure 11(a), (b) and (c) present the temperature inside of the container in System 1, 2 and 3, respectively. The inside of the container temperature difference between the systems are shown in Figure 11 whereby (d) is  $T_{\text{System 2}} - T_{\text{System 3}}$  and (e) is  $T_{\text{System 1}} - T_{\text{System 2}}$  which show the effect of the addition of water and PCM on the inside of the container temperature.

The recorded temperature inside the container of System 1 (PV/T/PCM), presented in Figure 11(a), was the lowest of all the temperatures inside the systems' container due to the PCM absorbing the thermal energy made available by the PV. Figure 11(b) and (c) shows the inside container temperatures of System 2 (PV/T) and 3 (PV with container). The temperature inside

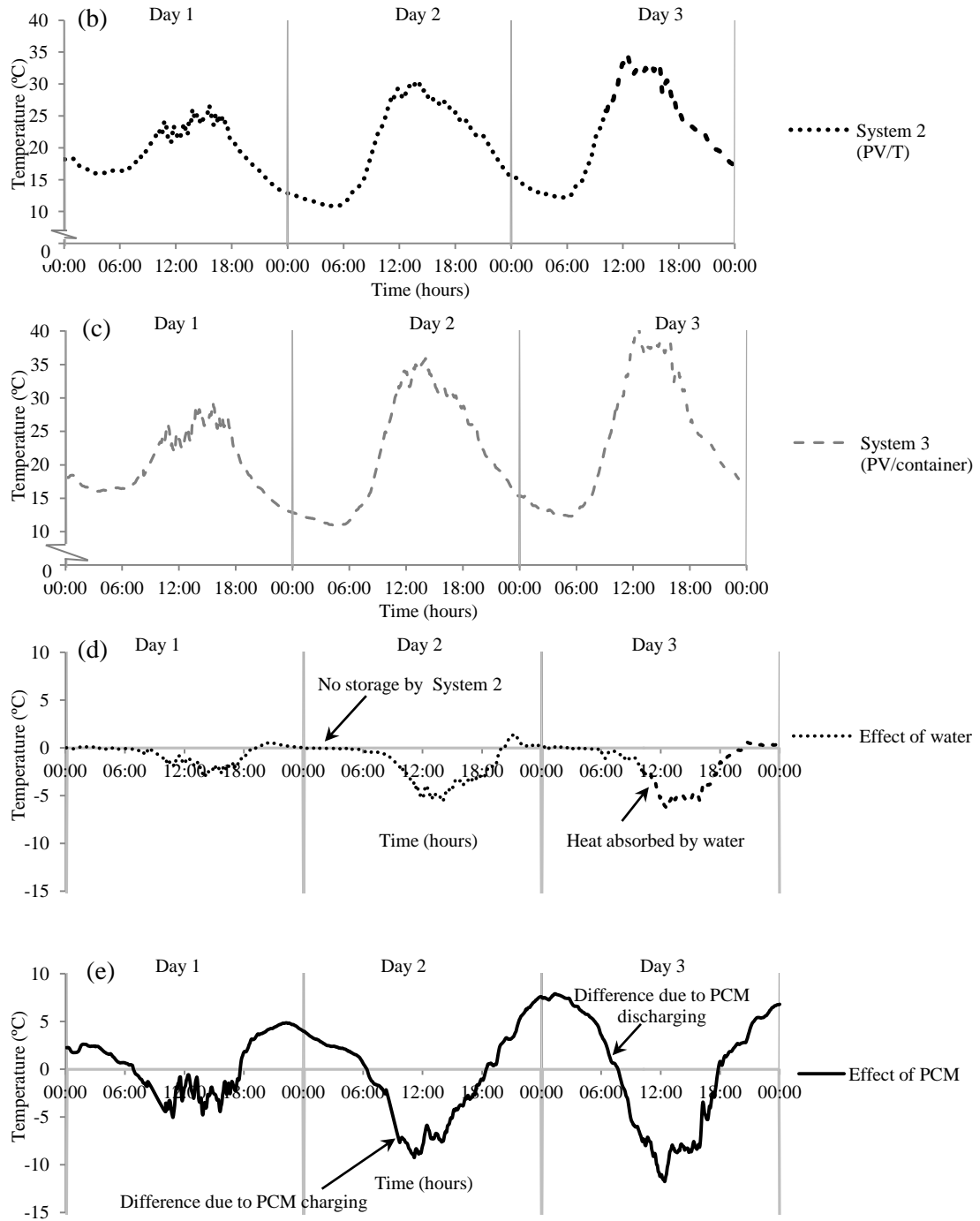
System 2 was lower than that of System 3 due to the transfer of heat energy from the inside of the container to the water.

The difference of the temperature inside the containers of System 2 and System 3, shown in Figure 11(d) shows the water removing heat from the container immediately from approximately 8:00 hrs to 18:00 hrs.

System 1, the PV/T/PCM system, stores heat for an extended period of time that can be used for space and water heating applications at a later time. The PCM was charged during the day and discharged between the hours of 18:00 and 6:00 hrs when the heat was transferred to the water. As a result the temperature inside the container in the PV/T/PCM system was lower than the other two systems between 6:00 and 18:00 hrs as it is absorbing thermal energy, whereas the temperature is higher between 18:00 and 6:00 hrs as heat is being discharged. Figure 11(e) shows PCM extended the time for which the heat was available allowing for a shift in the peak load from daytime, approximately 8:00 to 18:00 hrs, to the early hours of the morning, 18:00 to 6:00 hrs.



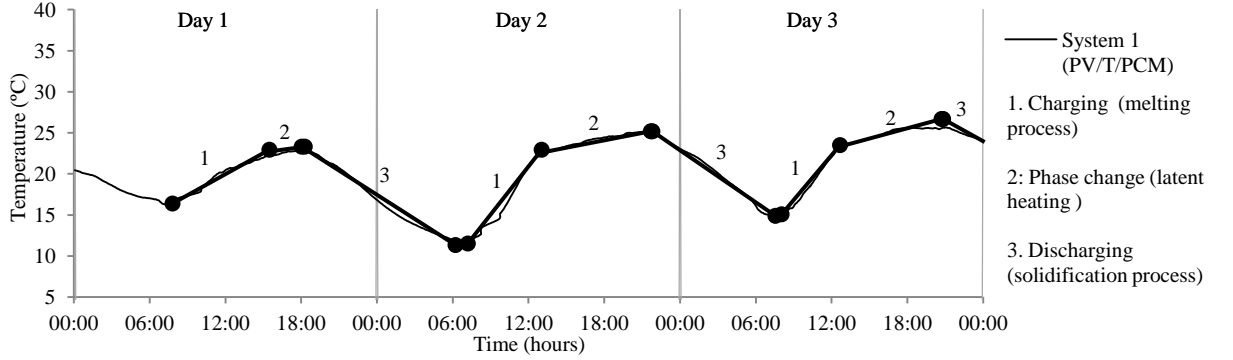




**Figure 11: Internal container temperature in (a) System 1 (PV/T/PCM), (b) System 2 (PV/T) and (c) System 3 (PV/container) and the effect of (d) the water and (e) the PCM on the internal container temperature**

The melting and solidification process of the PCM in System 1 demonstrates the material heating latently as in Figure 12. The material initially heats sensibly (System 1) on the morning of each day where it is increasing linearly. At point 2, the material is charging as the

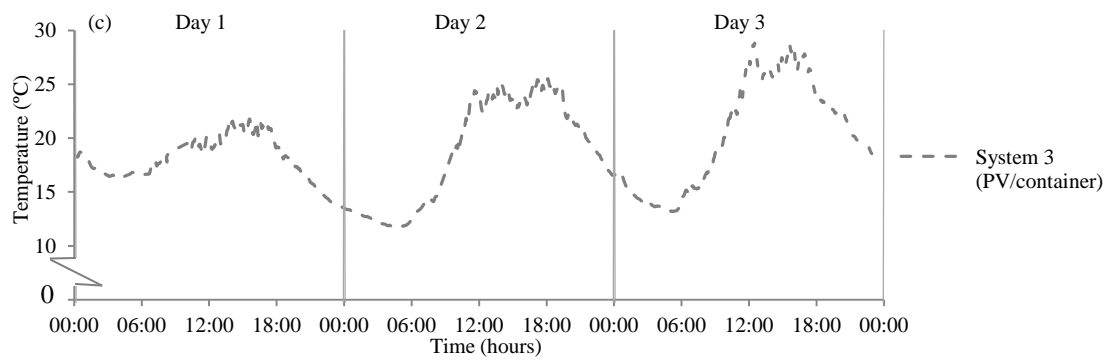
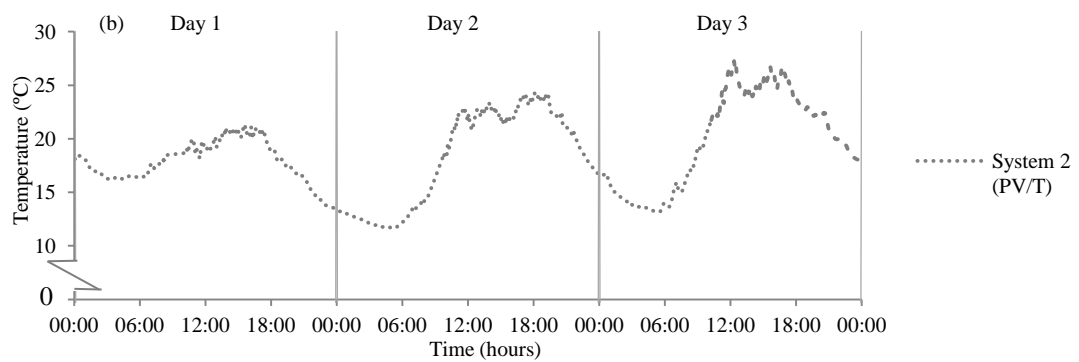
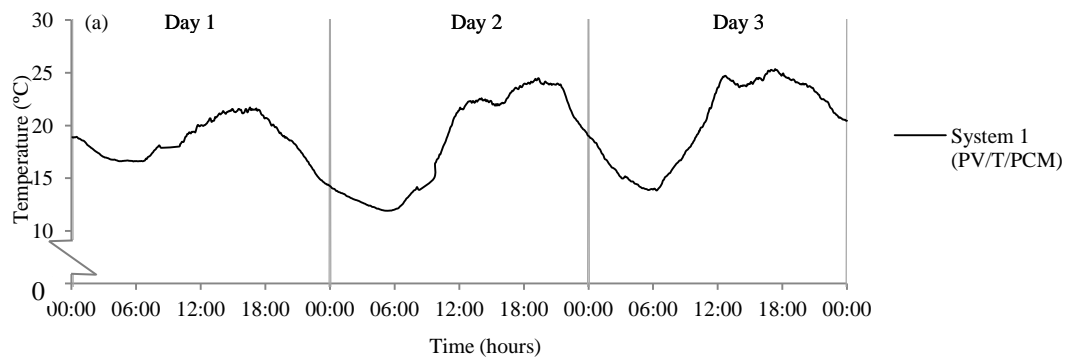
slope of the heating curve is increasing at a much slower rate and finally during the evening the discharging of the PCM is taking place as the curve descends rapidly.

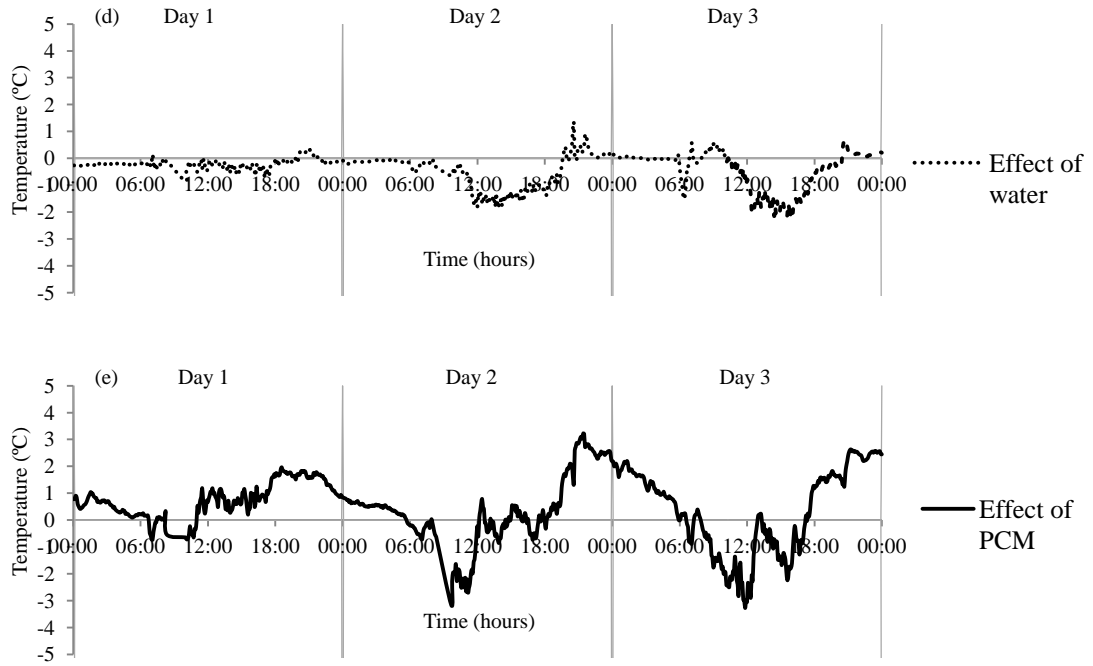


**Figure 12: The charging of PCM for the duration of the three days, (1) sensible heating during melting, (2) latent heating over the phase change range and (3) discharging sensibly**

Ambient temperature has been shown to affect the ability of PCM to store thermal energy due to the heat transfer from ambient through the container to PCM. Therefore during discharging, the PCM can reach temperatures only as low as the prevailing ambient temperature. If the PCM did not reach temperatures below its solidification temperature it remained in a liquid state, with no capacity to latently store thermal energy the following day. This is seen on Day 3 in Figure 12 as the temperature of the PCM has reached just below 15 °C compared to Day 2 where the temperature of the PCM reaches approximately 11.5 °C. The charging process took an average of 10 hours based on the three days presented; however, the length of time for charging was obviously dependent on the environmental conditions. The system presented would be suited to a climate with clear skies at night to avail of solidification by radiative cooling to night skies with minimal cloud cover. However, the importance of selecting both a material with a suitable phase change temperature and an appropriate effective means of heat exchange to the PCM should be emphasised because if the ambient temperature is too low, the PCM would discharge much earlier in the night, thereby losing some of the stored heat to the environment. This would be detrimental to satisfying morning water heating loads, but beneficial for daytime PV cooling.

The temperature variation on the rear of the stainless steel container gives an indication of thermal losses from the container to the environment. The back container temperature differences between the systems are shown in Figure 13 whereby (d) is  $(T_{\text{System 2}} - T_{\text{System 3}})$  and (e) is  $(T_{\text{System 1}} - T_{\text{System 2}})$  which represent the effect of the water and PCM, respectively. The losses from System 1 were higher due to the increased temperature difference between the back of the panel and ambient compared to System 2 as in Figure 13.

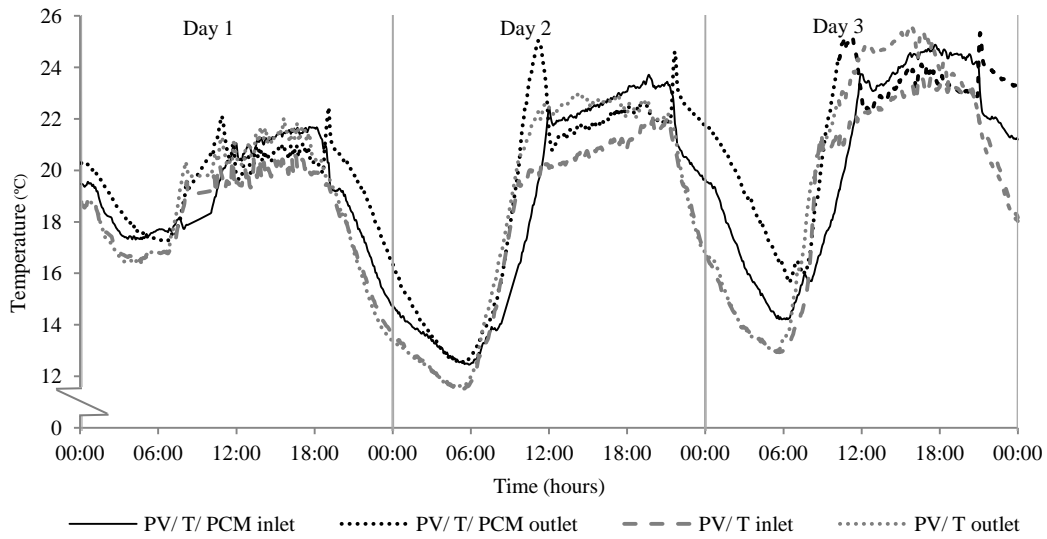




**Figure 13: Temperature of the back of container in (a) System 1 (PV/T/PCM), (b) System 2 (PV/T) and (c) System 3 (PV/container) and the effect of (d) water and (e) the PCM on the temperature of the back of the container**

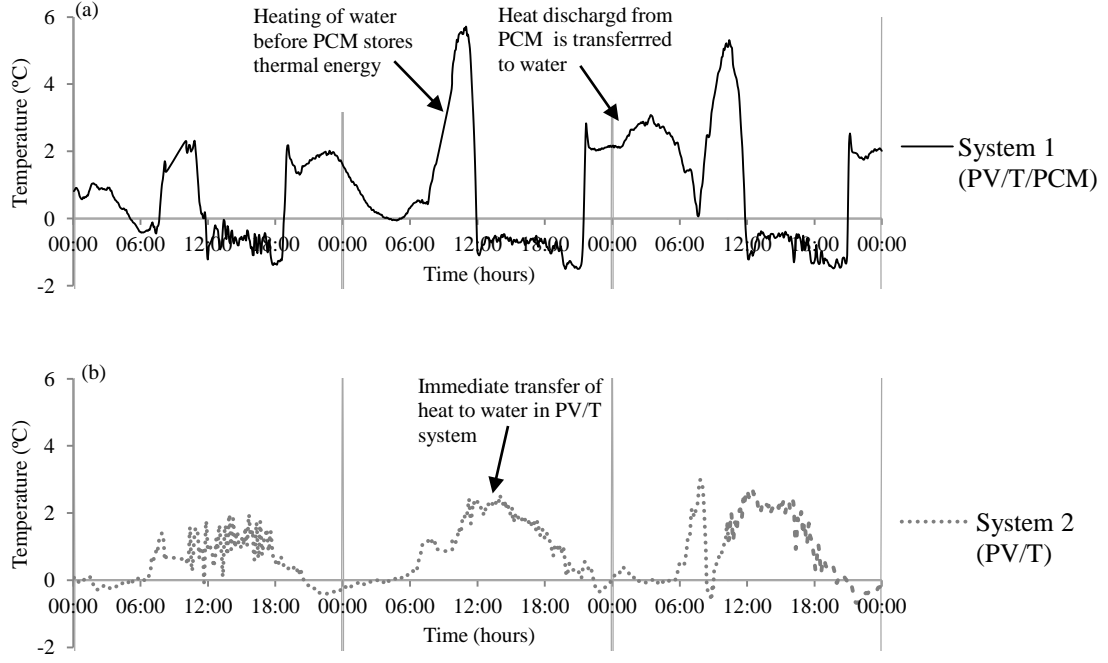
The temperature of the water at the inlet and outlet pipes in System 1 (PV/T/PCM) and System 2 (PV/T) is shown in Figure 14. The daily temperature variation of the water in System 1 shows the heat generated by the PV being stored by the PCM during daylight hours (approximately 12:00 – 20:00 hrs) as the change between the inlet and outlet of the thermosyphon was an average of 0.8 °C. During the daytime, it can be seen that the inlet temperature exceeded the outlet temperature by an average of 0.8 °C, which would suggest that the PCM was absorbing thermal energy from the water. It is worth noting that although this energy was being relocated from the water to the PCM, it was not lost, as the majority of energy stored in the PCM would eventually be extracted from the PV panel into the water. As the ambient temperature decreased at sunset, the PCM began to discharge, transferring the heat to the water as illustrated in Figure 15(a) where the temperature of the water increased (approximately between 21:00 – 10:00 hrs). Prior to beginning to store heat, the PCM heats sensibly; the temperature of the water reading an initial peak at approximately 10:00 hours where the water was being heated before the PCM begins to store the heat.

The temperature of the water in System 2 (PV/T) increased during the day (approximately between 9:00 – 18:00 hours) as the heat generated by the PV was absorbed directly by the water as in Figure 15(b). System 2 (PV/T) should make use of the heat available instantaneously to avoid it being lost to ambient.



**Figure 14: Temperature at the inlet and outlet pipes in System 1 (PV/T/PCM) and System 2 (PV/T)**

The temperature difference between the inlet and outlet in each system as illustrated in Figure 15(a) and (b) shows the water was 5.5 °C higher in System 1 (PV/T/PCM) at 6:00 hrs than that in System 2 (PV/T). For many domestic dwellings, unoccupied during working hours, 6:00 hrs would be a better suited time for pre-heated water supply than midday, when the water temperature was at its highest in System 2 (PV/T). The PCM can be seen to draw thermal energy from the water during the day as shown in Figure 15(a) however the advantage of a PV/T/PCM system over a PV/T system is the potential to shift in the time of availability of thermal energy. The thermal energy was not lost in this case; it was merely relocated to the PCM to be discharged to the water at a later time. The water in System 2 (PV/T) was only preheated by up to 2.5 °C, less than half of the maximum temperature increase in the PV/T/PCM system. The PV/T system has the advantage of allowing for the immediate availability of pre-heated water during the day as there is no storage within the collector.



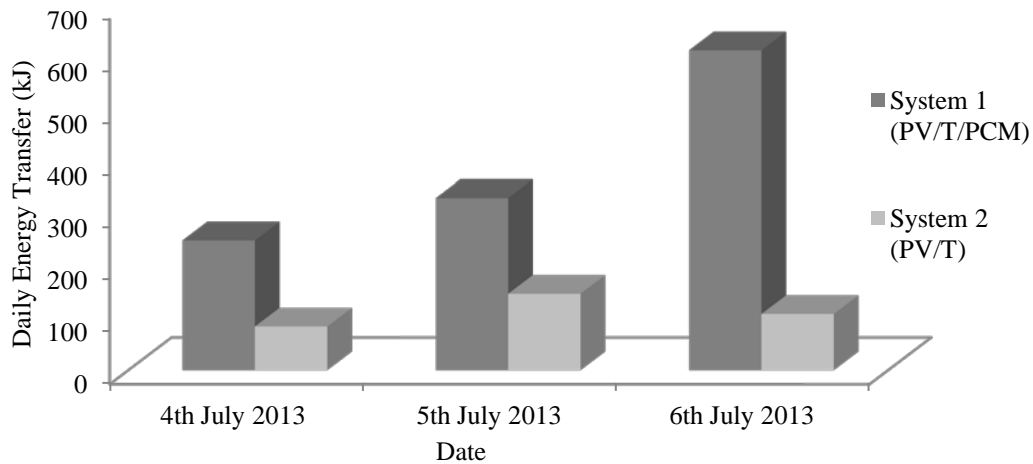
**Figure 15: Temperature difference of water at the inlet and outlet of (a) System 1 (PV/ T/PCM) and (b) System 2 (PV/T)**

The advantage of the integration of PCM into a PV/T system is evident by calculating the useful energy,  $Q_u$ , using equation 1.

$$Q_u = \dot{m} C_p (T_o - T_i) \quad (1)$$

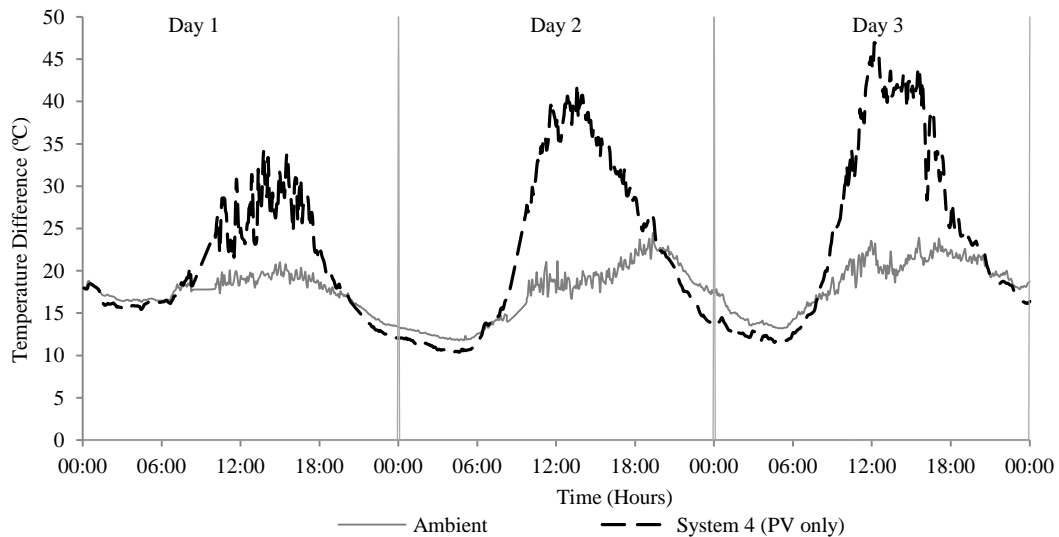
Where,  $Q_u$  is the useful energy (kJ),  $\dot{m}$  is the daily mass flow rate of water (kg),  $C_p$  is the specific heat capacity of water (kJ/kg.K) and  $T_i$  and  $T_o$  are the water temperatures at the inlet and outlet, respectively. Figure 16 shows the daily thermal energy transferred to the water in System 1 and System 2. The addition of the PCM can be seen to increase the heat transfer as it occurred over a prolonged period of time due to the heat storage of PCM in System 1.





**Figure 16: Daily energy transfer to water in System 1 and System 2**

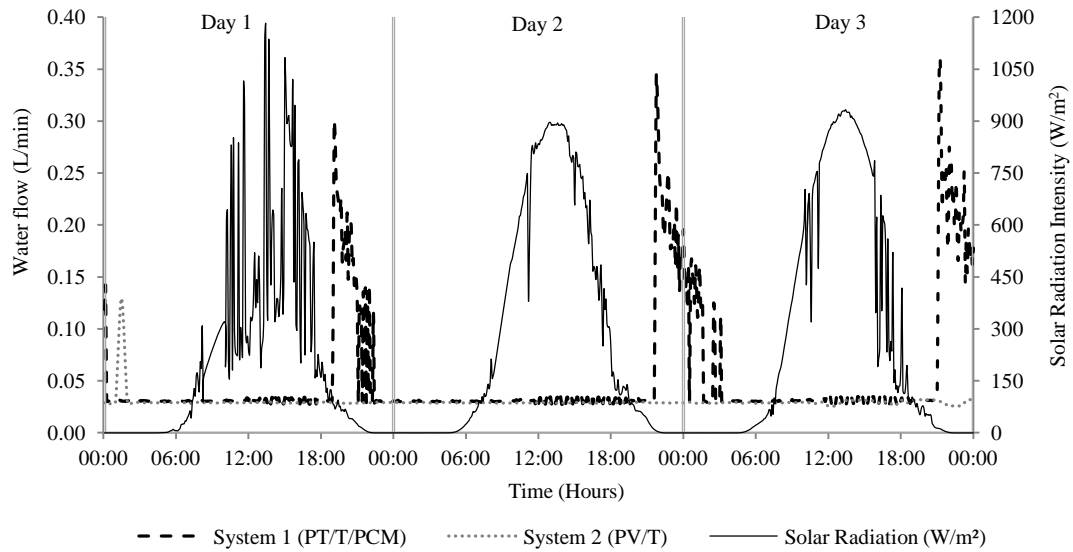
The temperature within the container was required to fall to 12.3 °C (as indicated by DSC investigations) for the PCM to solidify thereby creating a heat sink for the PV panel the following day. If this was not the case, the PCM would have commenced the insolation period semi-melted and consequently it would melt completely sooner, thereafter acting as a thermal insulator. Figure 17 shows the lowest temperature reached on the back of the reference PV was approximately 12.3 °C for a very short period. This suggests the PCM was storing the maximum amount of heat energy on a daily basis as the PV temperature reached a significantly low temperature at night for the PCM to discharge fully to solidify.



**Figure 17: Temperature comparison of the back of panel in System 4 and ambient temperature**

These results agree that the solidification range of the PCM capric: palmitic was between 12 °C and 17 °C as presented in Figure 1 and Table 2 in Section 2. During the days shown, the

PCM temperature reached lows of just above 11.5 °C which was sufficient to fully solidify the PCM to provide its full heat storage capacity during the next day.



**Figure 18: Flow of the water in the pipe network Vs Time Vs Solar Radiation**

Thermosyphon flow was low for the most part of the day as shown in Figure 18; however after sunset there was an increase in flow in the PV/T/PCM system. This movement was driven by the thermal energy stored in the PCM which was being discharged to the water causing an increase in flow. Heat transfer in the systems would be improved if the flow was increased for the duration of the day. It is possible to increase the height difference between the absorbers and the water tank to increase flow and thus the heat transfer. This would also increase fluid flow resistance. A pump can be used although this requires a power input (that would come from the PV), incurs an additional initial cost, requires associated sensors, control circuits and periodic maintenance.

The results show that the one main issue with the system, is that heat transfer from the PV to the PCM is gradual, if this process could be further improved the performance of the system would be enhanced and thus improve the economic feasibility of the system. A means of achieving this could be to increase the thermal conductivity of the PCM with carbon additives ([Choi et al., 2014](#)).

#### 4.1 PATHOGENIC BACTERIA

Heated water in tanks has to be maintained above temperatures specified in regulations to minimise the proliferation of pathogenic bacteria, such as *Legionella*. A PV/T/PCM system is envisaged to be a pre-heat system that would only be a part of a larger system in which an

auxiliary heater would be used to boost water temperatures to meet regulatory requirements if necessary.

## **5 CONCLUSION**

It has shown that the thermal performance of a PV/T/PCM system can be enhanced as water is heated to a higher temperature for a prolonged period of time compared to a system without PCM. For the particular system studied, the maximum temperature difference between the water in the system with and without capric:palmitic acid PCM was 5.5 °C and occurred at approximately 6:00 hrs. The integration of PCM has been shown to enhance the energy generated by a PV module due to its ability to regulate the temperature of the PV. The PCM has been shown to improve the extraction of thermal energy from the PV by up to seven times compared to a system without PCM. The energy storage by the PCM allows for the thermal energy to be used in other applications, such as heating water as shown in the article presented. Phase change temperature must be achieved overnight to allow for solidification of the PCM, to ensure maximum storage of heat during the day.

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